

Private/Public Research: Knowledge Assets and Future Scenarios

Gordon Rausser¹

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¹ Gordon Rausser is Dean, College of Natural Resources; Robert Gordon Sproul Distinguished Professor; and member, Giannini Foundation of Agricultural Economics, 101 Giannini Hall 3100, University of California at Berkeley, Berkeley, CA 94720-3100.

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Knowledge and know-how have always played a critical role in agricultural, resource and environmental systems (ARES). In our areas of expertise, as well as throughout American society, it has long been recognized that prosperity rests on knowledge and its useful applications. At the dawn of the next century, however, the source, the concentration, the distribution, and the use of knowledge could change dramatically. While this has been true for some time in other segments of the U.S. economy, it has only seriously emerged as a fundamental force in ARES over the course of this last decade of the twentieth century.

Knowledge is not homogeneous but a differentiated asset. Moreover, as Polanyi (1966) recognized, it's useful to draw the familiar distinction between tacit and codified knowledge. It is generally not possible to articulate tacit knowledge in any meaningful or complete framework. Such knowledge draws on skills and techniques that are acquired experimentally and are transformed by demonstration, apprenticeships, personal instruction and the provision of expert services. Such knowledge is slow and costly to transmit. Here within ARES, there are no noticeable changes in fundamental trends. This is not the case with regard to codified knowledge. This knowledge is reduced and converted into messages which can be easily communicated. The more codified are the components of knowledge assets, the more economically it can be transferred. Codification is simply a step in the process of reduction and conversion that renders the transmission, verification, storage and reproduction of knowledge all the less costly.

Within ARES, codified knowledge has assumed an increasingly important role. Such knowledge assumes the form of a non-rival good. In other words, sharing information will not reduce the amount of information possessed by the originator. This knowledge can be possessed and used jointly by as many as care to do so. This joint use, of course, satisfies one of the key features of a public good. This category of knowledge, however, is not a public good, as once it is produced it is possible to exclude access by others. This is certainly true of patents, copyrights, and trade secrets, means by which various agents can be excluded. It is this form of knowledge that portends dramatic changes in the industries where our collective professional expertise resides.

Knowledge is a durable good, with atypical characteristics. Although it decays with disuse, it tends to grow with use. It is frequently both consumption and a capital good. Its productivity can, in fact, confer on it an intrinsic worth. It can be both observable and nonobservable in use. Some knowledge is observable once a transaction has been recorded. For process technologies, however, this is often not the case. While the fingerprint of a process embedded in a product may be ascertained through reverse engineering, this is often not possible if knowledge owners are diligent in protecting their trade secrets. Finally, there is a vast literature that draws distinctions between embodied and disembodied knowledge (Sunding and Zilberman).

In the generation and distribution of knowledge, useful distinctions can be drawn between science and technology. Science is often viewed as a non-market allocation mechanism where knowledge is treated as a pure public good. In contrast, technology is a market allocation mechanism where knowledge is treated as a private good and where patents, copyrights, and trade secrets preserve property rights. In science, the presumption is that discoveries must be disclosed completely and speedily. For technology, however, findings might not be fully revealed, either immediately or even eventually to society at large. At the risk of oversimplification, science aims at increasing the stock of knowledge by encouraging originality, while technology seeks the rents that can be earned from this knowledge.

Within ARES, as the pendulum has swung more intensely in the direction of codified knowledge, serious implications exist for structure, conduct and performance. As a profession, we must muster all that modern economics, modern finance, modern industrial organization, modern science, and information based technologies have to offer to capture the fundamental forces that will dictate the evolution of ARES. This paper represents one small step in this direction. In making this step, the roadmap that will be followed will focus on the creation of

knowledge assets, the market for knowledge assets, capturing value from such assets, as well as the causal forces that will determine future wealth and quality creation (Figure 1).

Knowledge Creation

The creation of new knowledge occurs through multiple processes and takes many forms and shapes. Innovations that result in new knowledge are often analyzed as research-and-development (R&D) processes within either the public sector or the private sector. In the twentieth century, the public sector has played a major role in supporting R&D efforts, enhancing ARES's knowledge base. In the private sector, R&D efforts have steadily expanded and over the course of the last decade and have exploded in the area of agricultural biotechnology.

One study after another has demonstrated that publicly funded agricultural research experiences annual rates of return of at least 35% (Fuglie, et al., 1996). Even so, federal government expenditures for R&D have not grown in real terms since the mid-1970s. In 1940, agriculture received almost 40% of the federal R&D budget, but by the 1990s its share had declined to less than 2%. In contrast, between 1960 and 1992, private spending for food and agricultural research tripled in real terms. Since 1992 it has expanded at an even more rapid rate. In the last year alone, commitments were made by private companies in the area of plant genomics that were approximately equivalent to the total private R&D expenditures in 1992.

Nowhere have these unfolding trends in public vs. private sector R&D commitments been felt more dramatically than at research universities throughout the country. Developed-country governments have held steadfastly to the conviction that basic science is a public good and that much of it should be conducted at research universities. Moreover, governments over the past decade have generally attempted to spare university support from cuts they have inflicted on their own research laboratories (David, 1997). These trends in private versus public research support, when confronted with the significant increases in the cost of scientific research (especially modern molecular biology) have naturally resulted in public-private collaborations.

Faced with trends in public support, the critical land grant university component of the U.S. agricultural science establishment faced significant downsizing through the 1980s and the early 1990s. As a result, land grant universities looked longingly toward the private sector to maintain and enhance their respective research capacities. Questions arose, sometimes with justification, sometimes without, about land grant university agricultural research being overly influenced by private interests. Others argued that such arrangements offered new potential for encouraging socially relevant research and facilitating the transfer of technology.

Evidence was reported for the 1980s that many public-private agreements supporting directed R&D resulted in the "crowding-out" of public good research that would otherwise have taken place (Just and Rausser, 1993). This experience illustrated that without proper policy design and implementation, universities could become pawns of powerful private interests and that the unique contribution that land grant universities can and should make to the public good will be lost. As Just and Rausser (1993) warned: "Public/private partnerships cannot be allowed to leverage universities resources and divert research from public good outputs not produced elsewhere."

In the highly stylized model of public/private collaborationsⁱ, (Lyons et.al., 1996), the bargaining process between research administrators and private industry representatives was investigated. The focus was on the potential for "crowding out" and/or "crowding in" of public good research. Their results demonstrate that the phenomena of crowding out and/or crowding in depends critically on the structure of the bargaining problem between the two parties and the amount of

external public sector funding. Specifically, if the bargaining problem is structured appropriately in terms of benefits, cost, and performance, crowding in of public good research is possibleⁱⁱ.

Alternative Paradigms

For some years the general belief has been that there exists a linear evolution from public good or basic science to private or applied research (Bush, 1945). The simplicity of this perspective allows analytically tractable representations. The presumption that innovation processes follow a straight line from basic research (conducted in governmental laboratories and mainly at research universities) through applied R&D (conducted mainly by firms) is attractive to governmental policy makers and university administrators and, some would argue, self-serving.

An alternative paradigm is one that admits nonlinearities and recognizes the chaotic nature of research and development processes. Many analysts have documented the meandering path of innovations into the wider economy. These analysts have demonstrated that innovations emerge through a circuitous route (Ruttan, 1982); this route can not be codified and, many would argue, is impossible to measure. An extreme variant of this view has been proposed by Kealey (1996) who goes so far as to argue that innovation tends to drive basic science, not the other way around. Regardless, this alternative paradigm blurs the distinction that governments often make between basic and applied science. As a result, it also blurs the boundary between the research university and the outside world.

Economic Growth and the Bayh-Dole Act

New growth theorists argue that up to 50% of all U.S. economic growth over the last fifty years was due to investments in R&D. Future growth will depend on future research investment. It is unrealistic to expect that private industry will underwrite all the necessary basic research. However, even if there were unlimited tax dollars for pure research at universities, the resulting discoveries would do little good for the economy or consumers if not effectively ushered into commercial application. Most university patents represent discoveries that are remote from any commercial viability. Accomplishing "technology transfer" has always been one of the most powerful reasons for a bridge to private industry (Parker and Zilberman, 1993). If it were not for public/private research partnerships, it is unclear when or if critical technologies such as lasers, protease inhibitors, and bioengineering would have made their way into the marketplace.

The linkage between discovery and innovations at research universities and the capture of commercial market value that ultimately promotes U.S. economic growth motivated the Bayh-Dole Act of 1982. Supporters of this legislation successfully argued that unless universities have the right to license patentable inventions, many discoveries from federally funded research would never become commercialized. Put simply, the act creates the incentives needed to bridge the creation of value with its capture. This act is, in effect, a transfer of property (intellectual) much the same as the rights allocated by the Land Grant Act that established public universities in each and every state.

An indication of this act's success is revealed by the results of a recent survey of university technology managers that indicate that licenses executed by universities increased 75% between 1991 and 1996, with 13,807 executed over this entire period (Association of University Technology Managers, 1997). Furthermore, patent royalties accruing to universities have more than doubled over a period of five years. In 1997, universities and research institutions received \$611 million in licensing fees, up from \$248 million in 1992.

Berkeley/Novartis Research Alliance

The question is not whether universities must deal with the outside world but how effectively they will do so. In this respect, the Berkeley/Novartis agreement provides a unique model for maximizing the benefit to research universities and therefore to the public. Typically, the

university and its faculty wait passively until they receive Requests for Proposals (RFPs) from governmental agencies or private companies and then generate a response on the other party's terms. As a result, they must live with, and never dictate, the critical terms of the relationship. By contrast, we staked out our strategic advantage, took the central position in the bargaining process, and inverted the typical protocol; it was the relevant faculty that generated the RFP, allowing private companies with R&D interests in plant biotechnology to respond, guided by our principles and on our specific terms. Contrary to prior practice, the alliance was structured by Berkeley, and the corporate candidates were asked to compete among each other to meet its conditions. The principles established by the faculty included finding an optimal fit between the research objectives of our faculty and the private research goals and established intellectual capital of our partner, maintaining absolute faculty freedom and autonomy; obtaining otherwise cost-prohibitive technological resources for our faculty, and maximizing discretionary resources for our infrastructure and graduate programs.

Initially four companies responded with written proposals to our structured approach. After lengthy negotiations, Novartis was selected from the field of candidates in part because of its R&D strategy and also because of its cultural compatibility. Although the size of the dollar commitment was a major factor, it was far from the only consideration. Academic freedom, ownership of discoveries, and Novartis' adherence to university professional standards were all key components of the negotiations.

The initial \$25 million commitment of Novartis comes to participating faculty within the College of Natural Resources without restrictions. It is allocated to meritorious research proposals through a faculty peer-review process. This approach differs radically from most privately sponsored university research in which the funds may be used only for projects selected by the corporate donor. Even taxpayer research funding comes with some strings attached. Faculty almost never receive open-ended grants to indulge their curiosity but, rather, receive limited funding for specified projects. The beauty of the Novartis alliance is that it places the choice of research projects under faculty control rather than leaving critical decision making to legislators, bureaucrats, or corporate employees.

What Novartis receives for its \$25 million contribution is the right to negotiate to acquire at fair market value a percentage of discoveries that may result from research it helps fund. In other words, if there are no marketable discoveries or the university does not accept Novartis' offer to license them, Novartis will receive no commercial rights at all. Even without this agreement, Novartis, as a member of the business community, could approach the Office of Technology Transfer to negotiate licenses on any of the university's proprietary rights. On the other hand, the university will be a winner regardless of outcome, having obtained not only needed resources and possible intellectual property ownership but also, perhaps most important, access to Novartis' proprietary genomic databases, which are essential to Berkeley's cutting-edge research in plant and microbial biology.

Intellectual Property and Knowledge Markets

The Berkeley Strategic Alliance would not have been possible if major changes had not taken place in the assignment of property rights, both in the public sector as reflected in the Bayh-Dole Act, and the private sector. Many of the changes in the private sector relate to enforcement as well as the assignment of intellectual property rights. Here recombinant DNA technology and other discoveries of modern molecular biology have vastly improved the integrity of intellectual property. Property rights emanating from "bag-label contracts" as well as trade secrets enjoy more effective enforcement as a result of DNA fingerprinting.

The major structural change in assignment of property rights has emerged in the form of utility patents. Until 1980, the only legislation in the United States that protected the innovative

investments of plant breeders came through the Plant Patent Act of 1930 and the Plant Variety Protection Act of 1970. The first act protects asexually produced varieties, whereas the second act extends to sexually reproduced varieties. Until the landmark Supreme Court ruling in the matter of *Diamond v. Chakrabarty* in 1980 (447 U.S. 303 (1980)), plant-related inventions based on genes or cells from nature or applied to living organisms were viewed as natural phenomenon and thus unpatentable. In this matter, however, the court held that “anything under the sun that is made by man” is patentable subject matter. Specifically the court found that “the patentee has produced a new bacterium with markedly different characteristics from any found in nature and one having the potential for significant utility. His discovery is not nature’s handiwork, but his own; accordingly it is patentable subject matter under the section 101.” As a result, this decision broadened the reach of utility patent laws to encompass living organisms as patentable subject matter. Accordingly, utility patents are now granted in the United States for genetically engineered organisms, processes of transforming cells, and expressing proteins and the genes themselves. Note that protection provided Plant Variety Protection Act certificates have fallen significantly over the course of this decade from a high of over 300 awarded certificates in 1992 to less than seventy awarded in 1998. Over the same period, utility patents rose from forty-eight to almost 500 per year.

Markets for Science and Technology

The augmented strength in intellectual property regimes has provided the foundation for more active technology markets. To some degree, this has spilled over to markets for scientific knowledge. This should not be surprising. Over the last decade, with the rapid liberalization of markets and the creation of many types of “intermediate” products, what is tradable has expanded significantly. This is especially true in security markets where derivatives, index futures, securitization, exotic options, barrier options, and an array of put and call options on both listed and non-listed assets, are actively traded. The sudden burst of such markets has been aided by developments in computer and information technology.

Under the alternative nondecomposition paradigm, integrating forces exist between pure science and marketable technologies. In particular, successful executors of technological knowledge often need to be well versed in the development and acquisition of upstream knowledge. Such technological sophistication on the part of purchasers in knowledge markets often requires significant in-house fundamental research capabilities (Cohen and Levinthal, 1989; Rosenberg, 1990). As increasingly knowledgeable buyers internalize fundamental research, the position of specialized technology producers is naturally diminished. Nevertheless, the vertical integration between research and technology production has been supplanted to a large degree, beginning in the 1980’s, with the growth of specialized technology suppliers.

For codified knowledge, knowledge and information are largely synonymous. For this form of knowledge, the traditional nexus between the economics of goods and services and the economics of information is decoupled. To be sure, sufficient information can be collected over the Internet to enable customers to engage in comparative shopping at significantly lower transaction costs. As a result, traditional marketing and distribution channels are under siege. In many instances, more “virtual” structures are viable with new information technology facilitating specialization. In some channels, the erosion in knowledge or information control, combined with the decrease in customer switching costs, will result in the emergence of niche markets.

With the decoupling of information from goods and service flows, information is commonly sold in bundles (e.g., magazines are bundles of articles and subscriptions are bundles of magazines). The advantage of customized bundles is that it reduces dispersion in users’ willingness to pay. When a supplier’s span of control covers sufficient information necessary to bundling, this can be attractive. This is especially the case where complementarities naturally arise. Information components can be guaranteed to be effectively integrated and there are some economies of

scope from combining the various component parts. Accordingly, the price of the bundle is typically less than the sum of the component prices.

The significant interest in the markets for technology and the recent focus on intellectual property in ARES is driven by the well-known phenomenon of increasing returns. To the extent that the phenomenon of increasing returns is operative in ARES, the Marshallian and Hickian frameworks of how markets operate and how firms compete must be revisited. These well-designed traditional analytical frameworks, which presume diminishing returns and increasing marginal product costs, do not hold for knowledge-based industries (Arthur (1988, 1996), Milgrom and Roberts (1990), Teece (1986)). In particular, as Arthur (1996) has argued, "John Hicks warned that admitting increasing returns would lead to 'the wreckage of the greater part of economic theory.' But Hicks had it wrong."

Products generated from knowledge-based industries incur large fixed costs and inconsequential, in many instances, zero marginal cost. This phenomenon exists in agricultural biotechnology and generally in the development and use of information technologies; the first copy can cost hundreds of millions of dollars with the cost of the second and subsequent copies zero or nearly zero. In this setting, the typical analytical frameworks and standard comparative static results are no longer relevant. Instead, non-convexities prevail and we are forced to turn to supermodularity frameworks (Milgrom and Roberts, 1990).

Increasing returns are driven by several factors: technology, standards and network externalities, the existence of tacit knowledge, and customer lock-in. The form of the technology drives the relative fixed and marginal costs. Network externalities and standards focus on critical customer mass. Once critical mass is achieved, network externalities (Katz and Shapiro, 1985) establish the basis for positive feedback economics and bandwagon effects. Here, consumer expectations are critical; perceptions drive what ultimately becomes the competitive standard in the minds of customers. If such standards are proprietary, those entities establishing the dominant standard can reap significant rents. As we see again and again in information technology, customer lock-in arises from significant switching costs. These costs are sourced in customer investment in knowledge accumulation.

Market Limitations

With the complexity of knowledge markets, new products are rarely stand-alone. Instead, they are components of integrated systems. Dependence on such integrated systems means that firms must focus not only on their competitors but also on their collaborators. As Arrow (1962) noted some time ago, in order to buy information, there already must be a significant stock of accumulated knowledge. As Mowery (1983) has found, it is generally impossible to internalize all R&D that is needed to integrate the technical know-how to arrive at marketable products. Accordingly, the demand for alliances, joint ventures and institutional arrangements has never been greater.

In biotechnology, the relevant intellectual property needed to bring specific products to the market is almost never owned or controlled, for that matter, by a single firm. As a result, serious problems arise with respect to the fragmentation of intellectual property rights. This fragmentation challenges the effective functioning of markets for technology. These limitations arise from "hold-up" and other forms of opportunistic behavior, informational asymmetries, and antistacking licensing arrangements.

From the standpoint of markets for technology, many plant biotechnology discoveries have been cumulative and systemic. Prior to much of the consolidation that has taken place in agricultural biotechnology, the pace of progress depended on the separable actions of many firms responsible for the production of needed components. Thus, in order for a particular firm to use the available

technology, that firm had to collect all the rights for the use of its components. In a world with no transaction cost, this would not be a problem, as we could expect the parties to bargain to a Pareto superior solution given any initial distribution of property rights over the components. In the realistic world of opportunistic behavior, holdup problems result in unrecoverable detours from such bargaining solutions. This has led to serious questions of “freedoms to operate” motivated by blocking patents or other forms of intellectual property.

In the presence of “blocking patents” market failures are often induced. In the case of complex fragmentation, there is little incentive for a system integrator to arrange transactions in the technology components sequentially. This is quite obviously because once the integrator has obtained some control of only a portion of the necessary components, the associated costs are sunk, and as a result bargaining power is diminished. The transaction cost faced in simultaneous transactions or even contingent transactions make this option almost impossible to execute.

Intellectual property fragmentation in agricultural biotechnology has experienced a number of patent infringement and patent validity lawsuits. Particular concern has arisen regarding property rights for isolated gene fragments. In a different context, but equally applicable to plant biotechnology, Heller and Eisenberg (1998) have argued that the proliferation of such patents held by different owners (and only licensed through stringent “pass through” provisions) results in a serious obstacle to research and the development of commercial products. For example, in the case of Roundup Ready Corn, nine critical patents must currently be bundled to deliver this product to the market. At one point, five major firms controlled one or more of these patents but as a result of mergers and acquisitions are now controlled by only two firms. This fragmented control has resulted in costly patent infringement litigation over the course of the last year.

Counters to the fragmentation problem include cross-licensing agreements, especially where large transaction costs are faced in any attempts to bundle patent portfolios needed for marketable products. A more effective solution that is yet to emerge in the agricultural biotechnology industry is patent pools.ⁱⁱⁱ Other institutional arrangements that have been used for copyrights, especially for artists and entertainers, are a potential solution. Ultimately, public policy is also largely responsible for the unintended consequence of intellectual property right fragmentation. Unfortunately, the U.S. Patent Office in Agricultural Biotechnology has issued overly broad and imperfectly specified patents. To be sure, this in turn is the direct consequence of the lack of expertise as well as the lack of necessary funding to search for and evaluate prior art.

Transaction costs and opportunism are the major sources of inefficient knowledge markets. Because of the increasing decoupling of information or knowledge from tangible goods as well as the fragmentation or non-existence of well-articulated property rights, it is no surprise that knowledge markets are often inevitably “thin.” There is an unfortunate paradox. For an exchange to be conducted efficiently, both buyer and seller must know with some precision the characteristics and attributes of what is being traded. However, once the information is assimilated by a potential buyer, the buyer might have no incentive to conclude the transaction; the seller cannot prevent the prospective buyer from benefiting regardless of whether confidentiality agreements have been signed. The difficulty of quantifying the value of knowledge without understanding its inherent attributes and characteristics was noted long ago by Arrow (1962).

A number of separate obstacles arise in the case of tacit knowledge. Here, the context dependent features of knowledge production as well as the significant cost of transferring technology across context can be a serious limitation. Consider for example producer learning and knowledge accumulation in the context of natural resource industries. As shown in Rausser (1974), Rausser, et.al (1972), and Rausser and Lapan (1979), knowledge augmentations can counter limitations of nature's endowments. In their frameworks, knowledge augmentations are endogenized as tacit

"learning by doing" processes in joint production, investment, pollution abatement, and consumption models. In the current context, their results demonstrate:

Proposition 1: Producer learning is internalized and its value can be captured but only by organizations that control the tacit knowledge.

The tacit knowledge accumulation process structured by "learning by doing" generates intermediate goods. There is very little transparency, with only some implicit imputed values associated with the indirect impact on productivity or intangible assets/goodwill appearing on corporate balance sheets.

Capturing Value from Knowledge Assets^{iv}

Creating knowledge is one thing, but capturing the value of knowledge is quite another. The existence of incomplete markets for technology provide no assurance that the potential value of new discoveries or innovations will be captured. Moreover, as economists have long realized, the questions of value capture turn on "appropriability regimes." Appropriability enhances value capture both when knowledge is inherently difficult to replicate and/or when intellectual property provides legal barriers to imitation. To the extent that replication and imitation cannot be accomplished, knowledge assets become the foundation for value capture through product differentiation.

Sources of Competitive Advantage

The inherent nontradability of many knowledge assets is a source of competitive advantage. This is especially true for tacit knowledge when coordination costs discourage outsourcing or virtual organizations and increase incentives for internalization of R&D activities. Specialized tacit knowledge assets create rents for their owners. As a result, imperfections in the market for know-how can be both a blessing and a curse.

In the case of codified knowledge, the strengthening of intellectual property is the most effective counter-force to imitation. If such assets are marketable, they can be accessed by all agents. Accordingly, the domain over which competitive advantages can be structured narrows as markets expand. For well-articulated intellectual property, however, it is indeed difficult to infringe without significant penalty even though it can be traded, in some cases reverse engineered and in others invented around.

As markets for codified knowledge expand, new competitors emerge, and rents normally accruing to the innovator dissipate. Licensing of such knowledge or technology generates royalty revenues or, in the case of agriculture, technology fees that must be balanced against the rent dissipation effect. The rent dissipation impact depends critically on the structure of the industry (i.e., the degree of control the innovator has in the product market). Where the technology rights are not controlled by a monopolist, a "commons" problem emerges in which profits from an oligopolistic market constitute the "commons" (Arora and Fosfuri, 1998).

Under this structure, the innovative firm that licenses its technology does not fully internalize the rent dissipation effect; the rent dissipation is shared with other users of the commons, whereas the innovative licensor is able to internalize the value of the license. Thus, it is quite possible for the revenue effect from licensing to outweigh any potential rent dissipation effect. This is especially true under well-articulated intellectual property rights that lower the associated transaction cost of licensing. Such rights may also enable the licensor to capture not only the licensing revenues but also a larger share of the rents. However,

Proposition 2: To the extent that broad intellectual property rights result in greater product differentiation, licensing will decline.

This is because if the licensing firm creates a rival who sits closer to the licensor in the product space than other product suppliers, the rent dissipation effect is internalized to a greater extent. Furthermore, as we've witnessed in agriculture,

Proposition 3: Trait developers that lack downstream assets to operate final markets sell more licenses.

Simply, such technology suppliers have no rents to dissipate under more intense downstream competition. In markets in which there are many innovators and many potential licensors, including universities, the rent dissipation effects will necessarily arise. As a result, in this world:

Proposition 4: Licensing by rivals increases the propensity of other technology holders to also enter into licensing agreements.

Under these circumstances, the markets for technology can become quite robust, once they arise.^v

Knowledge Assets and Conservation

An important example of knowledge value capture to environmentalist and much of the developing world is bioprospecting. This activity has been touted as a source of finance for biodiversity and environmental conservation. In a world of no knowledge assets or informative priors, the value of the "marginal unit" of genetic resources is likely to be vanishingly small, creating essentially no conservation incentives. However, ecological and taxonomic knowledge can change the beliefs about potential locations of genetic materials that are candidate sources for the development of new products. In this search, leads of unusual promise are distinguished with the aid of scientific information gleaned from biological and ecological science. Such knowledge developed by researchers, when filtered through a model that provides differential success probabilities, can serve to tag those creatures most likely to display economically valuable characteristics.^{vi}

As demonstrated in Rausser and Small, 2000, when search procedures are optimized to take advantage of knowledge assets through useful prior information, high probability leads command information rents associated with their contribution to the chance of success. Such knowledge allows search costs to be avoided. These rents augment any scarcity rents arising from any bound on the total number of leads available for testing. From this analysis, the following proposition emerges:

Proposition 5 – The magnitude of information rents depends on the degree to which ecological and taxonomy knowledge turns leads into "differentiated products," creating a monopolistic competitive market in research opportunities. Rents for high- quality leads can be significant even when the aggregate supply of genetic materials is large.

When biological resources are abundant, an increase in the potential profitability of product discovery has virtually no effect on the value of any lead, whereas technology improvements at lower search costs induce (weakly) a decline in the value of every lead. Empirical analysis suggests that bioprospecting information rents can in some cases be sufficiently large to finance meaningful biodiversity conservation.

Value Differentiation in Agriculture

Intellectual capital and property rights are the foundation for transforming traditional agriculture from a commodity business to a differentiated product business. This transformation has been referred to as the value differentiation process (Goodhue and Rausser, 1997). Readily available public knowledge, with no differentiable property rights, has long been the source of a commodity business in agriculture; costs are what they are, and demand is what it is; neither respond to the heterogeneous efforts of market participants. For a differentiated product, however significant resources are devoted to "developing a market for" or "capturing the value of" the product. It is not enough simply to supply the product; one must also create a

differentiated demand. By the same token, for a commodity, the fixed operating cost that a producer faces is truly fixed, whereas for a differentiated product the magnitude of these fixed costs can be modified by management effort.

As the agriculture and food industry shifts from homogeneous commodities to heterogeneous products, the mass consumer markets developed over the course of the twentieth century can be expected to fragment along specialized product niches. Increasingly, food processors and retailers must precisely identify their targeted consumer groups in order to compete successfully in a value-differentiated market environment.

Rapid improvements in information technology will facilitate this marketing shift toward improved quality control and more cost-effective production at all levels of the agrofood chain. The Internet has only begun to facilitate serving consumer niche markets with suitably customized products. Biotechnology can be anticipated to further lower production costs and increase the ability to control product attributes. There are indeed synergies across these two sources of emerging technologies. In essence, value differentiation is the process by which agrofood chain agents match and exploit heterogeneity in consumer preferences and in product attributes. The product heterogeneity can originate at any stage of the production and distribution process.

The interactions and causal links at the heart of value differentiation can be captured analytically by supermodularity frameworks. These frameworks admit increasing returns. Supermodularity does not impose convexity, or the typical diminishing marginal returns, or increasing marginal cost relationships. The focus of supermodality frameworks is on the joint undertaking of activities that create benefits that cannot be realized by taking each activity separately.

Supermodality is a promising framework for integrating the methodologies used in agricultural economics with those used in agribusiness. Agricultural economists have emphasized analytical solutions focusing on conventional marginal techniques, whereas agribusiness has emphasized a systems orientation that is long on description and short on analytical structure. Supermodality captures the intuition of agribusiness professionals who observe changes in production, organization, marketing, and management practices that tend to occur in clusters. As a result, it is difficult to assign causality and the typical convexity assumptions of agriculture economists are violated.

Historically, much of the value differentiation in agrofood industries has occurred downstream. With the augmentation of knowledge assets through new developments in biotechnology and information technology, it is distinctly possible for differentiated products to emerge at earlier stages of the vertical marketing chain. The potential development of quality enhancing (output) biotechnology traits could allow differentiation through production, processing, and marketing distribution components. The Internet has the capacity to accommodate differentiated products at any stage of the vertical marketing chain.

Complementary Assets

Any efforts to imbed knowledge in differentiable and marketable products must confront the issue of access to complementary assets. Successful attempts (to succeed) in the value differentiation process will depend not only on the appropriability of innovation rents but on access to complementary assets. If such assets are already controlled, no obstacle need arise. However, because the market for complementary assets is itself riddled with imperfections, such assets might become the "choke point" in the value chain. It is, in fact, the integration of complementary assets and the need to identify the incremental returns of their components that are the focus of supermodularity frameworks.

In the case of recent technological advances in agriculture, the complementary assets include, *inter alia*, research capacity, scale up experience, and access to seed research stations.^{vii} As noted by Graff, et.al. (1999), research or process technologies for plant transformation, access to traits and enhancements of elite germplasm, capacity to produce nonbiological agricultural inputs (herbicides), distribution network for seeds and other inputs and legal and regulatory competencies are among the crucial complementary assets.

Any knowledge innovation rents will depend on a particular discovery's appropriability as well as the degree of specialization of complementary assets. If access to complementary assets is available through open market transactions, the innovator will capture the rents. To the extent that this is not true, specialized complementary assets will capture a share of such rents. Obviously there are varying degrees of innovation, appropriability and the control of complementary assets (Teece, 1986).

The number and the complexity of contracts, joint ventures, and strategic alliances with other firms in the industry and with universities and other non-profit research institutions have increased the value of the complimentary legal and regulatory competencies. New institutional arrangements, such as grower license agreements introduced by Monsanto to protect and capture intellectual property value, have resulted in an unprecedented number of legal claims (grower alleged violations through saved seed). The monitoring and enforcement of refuge requirements to manage potential insect resistance buildup is another element of legal and regulatory competencies. The net result of all these activities is to increase the entry barriers and thus often to keep imitators and other potential innovators at bay.

Intellectual Property and Market Structure

Intellectual property rights do not, by themselves, ensure the capture of value. This can be either because complementary assets are not combined efficiently (Teece, 1986) or because the joint profit available from an accumulative line of research is not divided such that the R&D costs of each innovator is covered (Green and Scotchmer, 1995). Both problems are especially critical in agricultural biotechnology from the standpoint of complementary assets. Even if a new and valuable trait is protected by a utility patent, it cannot generate value without being incorporated in the germplasm that is produced and sold to farmers.

Much has been written on the rapid consolidation that has taken place in agricultural biotechnology over the current decade (Rausser, Scotchmer, Simon, 1999). In the popular press and industry publications, a number of hypotheses have been offered to explain this consolidation. One group of hypotheses focus on contractual hazards associated with licensing, avoidance of appropriability hazards, and uncertain intellectual property rights. Given the scope of some patents issued in plant biotechnology, there are justifiable concerns that holdup strategies will be rampant. The second group of hypotheses is sourced with the exploitation of asset complementarities. The critical assets include "freedom to operate," enabling process technologies, bundled products (Roundup ready seed and the herbicide), and elite germplasm. To the extent that such complementarities lead to significant efficiencies, augmented R&D budgets, and enhanced innovation is an expected result. A third category of hypotheses focuses on anticompetitive behavior and the quest for market power. Here, the regulators (the Department of Justice and the Federal Trade Commission) face serious challenges. In the case of agricultural biotechnology, evaluating preconsolidation conduct and behavior in a world of commodities provides little, if any, insight into conduct and behavior in a differentiated product world.

Another explanation for the consolidation that's taken place among life science, seed and biotechnology R&D companies is the distinctly different views and beliefs about the nature of complementary assets and how bundled products might be created. At least in the case of Monsanto, one clear incentive to create transgenic plants was to protect its position in the

herbicide market for its branded product Roundup. This patent comes to an end in the year 2000. Unlike trait developers who might simply receive revenue from licensing of their technology, Monsanto has a strong incentive to make sure that its Roundup-ready technology traits also maintain and boost sales of Roundup.

A hypothesis has been recently introduced (Rausser, Scotchmer, Simon, 1999) to formalize this explanation for selecting the "merger" option instead of different forms of licensing. This explanation focuses on heterogeneous beliefs and the causal connection between intellectual property and the emerging increasing returns perspective with differentiated products. In all knowledge based industries, and agriculture is no different, forces for increasing returns exist alongside those for diminishing returns. Moreover, there are critical segments of agriculture that continue to perform not as a differentiated product business but instead as a commodity business. For the latter, products are fundamentally homogenous, transactors can be anonymous, and markets are clearly delineated. For the former, the distinction between products and the boundaries between markets are blurred. Managers and entrepreneurs in the commodity world accept the notion of diminishing returns and the serious obstacles that are confronted as they attempt to expand. Because of the high degree of substitutability in this world, the value is more or less exogenously fixed with razor-thin margins.

Formally, consider a two-tier production process involving a trait developer and a seed producer. Vertical integration can be accomplished either by contracting (i.e. exclusive licensing) or by consolidation (i.e. mergers and acquisitions). To examine the possible causal connection with intellectual property rights, two regimes are admitted in the proposed industry structure: one with clearly articulated property rights and another regime in which such rights do not exist.^{viii} To examine the fundamental question of whether there is anything that consolidation can achieve that contracting cannot, a primitive model can be developed in which markets are open for two periods. In the commodity world, all market parameters are identical in each period. In the first period a single agent develops an R&D product called a trait incurring a substantial fixed cost and zero marginal cost. What happens in the second period depends on whether intellectual property rights are clearly articulated. If they are, the trait developer obtains a patent and retains his monopolistic status in the second period; if they are not, other suppliers will imitate the trait developer's product in the second period, and price competition will drive the equilibrium price of licenses and thus equilibrium profits for the trait developer to zero.

For the differentiated product world, the distinctions of heterogeneity are introduced through subjective distributions on the demand for transgenic seed and the fixed cost of producing the trait. Both the trait developer and the seed provider hold beliefs about these variables, and their subjective beliefs might vary, depending on each agent's vision, management controls, and production and marketing operations. The results demonstrate that under homogenous beliefs, consolidation and exclusive licensing contracts are equivalent routes to integration. Once heterogeneous beliefs about management are introduced, the equivalence between the two forms of integration breaks down. Under irreconcilable differences the distinction turns on the issue of control and control premiums. Provided that at least one party has sufficient faith in its own vision and strategy to warrant consolidation, the other will be willing to cede control in exchange for compensation that does not depend on a subsequent performance of the integrated enterprise. As a result, the following proposition holds:

Proposition 6: In a differentiated product world with a well-articulated intellectual property regime, many parameter values exist for which integration via consolidation is feasible but for which integration via exclusive licensing is not.

In the pristine setting of the model sketched here, intellectual property does effect incentives to vertically integrate either via consolidation or contracting in a world of differentiated products but not in a world of commodities. For the regime in which intellectual property rights do not exist, the differentiated product world leads to the same conclusions with regard to the merger verses

the licensing options as in the commodity world. Moreover, when such rights do exist and agents have heterogeneous beliefs about the causal determinants of industry profitability, there is a range of parameter values for which integration via consolidation will be profitable but for which integration via contracting will not.

Future Scenarios: Wealth and Quality Creation in the New Society

Like much of US society, ARES has become increasingly knowledge based. The deployment and use of knowledge assets will become more central to competitive advantage. The ownership of physical and financial capital will not determine fundamental value. Increasingly, agents throughout ARES will recognize that market value will be sourced principally with developing, protecting, and exploiting intangible assets (technical know-how, competencies, consumer loyalty, and intellectual property).

In addition to the usual knowledge asset risk (freedom to operate, litigation, and desire for privacy) agriculture biotechnology is especially vulnerable. This vulnerability is sourced largely with perception-based rather than objectively based risk. Nowhere is this truer than in Europe, where the term "Frankenfood" has entered the lexicon. The opposition of environmental activist groups has achieved some credibility in the minds of the general public as a result of the food scare over the "mad cow" disease in England; the dioxin in feed, poultry, beef, and butter in Belgium; and the most recent episode with Coca-Cola. These activists' organizations are concerned about the health hazards of genetically altered foods and the potential environmental hazards of insect resistant build-up. With the Cornell Monarch Butterfly study, the migration of B.t. pollen from one field to another, monoculture vulnerability to pests and disease, and the potential for "genetic erosion" in less developed countries are other concerns that have been expressed. Over the course of the next year, these concerns can be expected to intensify throughout much of the global community. In this regard, the most recent signal is a Brazilian court injunction prohibiting the planting of transgenic soybeans. These events have whetted the appetite of environmental activists.

Even in the face of perceived risk, as well as more objectively based risk, the newly restructured life-science companies have made commitments for private R&D funding in the United States that are orders of magnitude larger than commitments of the Federal government for plant genomics R&D (at least thirty times as large). Although there is certainly some reassessment of R&D plans by these companies, there has been no reversal of publicly announced commitments.

For the twenty-first century, there are critical forces that could well sustain the role of knowledge assets in improving productivity and enhancing the quality of life. There are also significant forces that could detract from these potential benefits. As any student of chaos theory will remind us, complex systems such as ARES can be changed radically by small disruptions that have dramatic ripple effects. Because of space limitations, I only outline here selected major forces that will dictate the scenarios that will actually emerge.

Major Forces

The experience of increasing returns will occur to some degree with separable developments in biotechnology and information technology. Precision agriculture will continue to evolve, providing greater transparency and traceability for all of its marketable outputs as well as its waste products. As we move downstream, opportunities for the supply chain and customers to become "Web-integrated" will be technically feasible. Web-based e-business will dramatically lower the transaction cost of suppliers and customers being brought together on-line. Depending on the advancements in biotechnology, the matching of prescribed food attributes and characteristics with specific consumer needs based on genetic diversity could become a feasible option.

The marriage one day of human genomics with plant and animal genomics could dramatically enhance not only the length of life but also its quality. The explosion of information about human genetic diversity offered by the Human Genome Project will allow many new research and development options for identifying novel genes that play key roles in chronic diseases and sustaining human health. The availability of microarrays of expressed sequences from different cells and tissues will allow the determination of the nutritional effects on gene expression at both the molecular and cellular level. Dietary effects on gene expression and DNA damage will establish a new field of research inquiry, nutritional genomics,^{ix} (DellaPenna, 1999). The agents who effectively exploit the complementarities among plant, animal and nutritional genomics have yet to emerge. However, this is part of the vision of the restructured life-science companies.

There are also potential complementary forces between biotechnology and natural technologies. The refuge prescription for dealing with potential insect resistance build-up might be complemented by biological controls. At this juncture, there is little evidence that either the private or public sector treats this as a serious research pursuit. This potential complementarity, when combined with information management, might well be the foundation for effective environmental risk avoidance of biotechnology applications. There are many agents that are promoting separate commercial development of each category of promising technologies but very few agents that have emerged that focus on the integration of complementarities among these technologies.

Public policy, in its many dimensions, will continue to be a major force in the evolution of ARES knowledge assets. The principle dimensions include competition, intellectual property, environmental food and health safety, and world trade policies. With regard to competition and intellectual property policies, inherent conflicts show little sign of being resolved. The clash between these two sources of protections has been amplified by the recent Microsoft and Intel cases. The clash has only begun to emerge with the role of utility patents in plant biotechnology and the associated fears of knowledge monopolization. The Department of Justice and the Federal Trade Commission have grappled with the mergers and acquisitions within ARES over the last five years and can be expected to confront even more serious challenges over the course of the next decade.

The pursuit of complementary efficiencies along with the accompanying increasing returns and in some cases even market power, will provide ample incentives for further consolidation and vertical integration. From the platform of integrated biotechnology trait/germplasm combined with an agricultural chemical product line, we can expect three strong competitors: (DuPont, Monsanto, and Novartis hotly pursued by Aventis, Dow and Zeneca). Each of these restructured companies may well vertically integrate downstream with food processors and end users through joint ventures, acquisitions, and/or strategic alliances. This has already happened with Monsanto and Cargill/Continental. Future announcements are expected that integrate biotechnology platforms with major food processors such as Archer Daniels Midland and ConAgra.

With the expected further introduction of output traits and ultimately commercialized "nutraceuticals," biotechnology will provide the foundation for still further integration between today's life science companies and the major players in the pharmaceutical business (e.g. Eli Lilly, GlaxoWellcome, Merck, Pfizer, and Schering-Plough). Strategic alliances with broad health related consumer product companies are also a distinct possibility (e.g. Abbot Laboratories, Bristol-Myers, and Warner-Lambert). The failed merger of Monsanto and American Home Products might well be a first small step in the direction of future mega-mergers that extend and legitimize the current vision of life science companies to food, nutrition, and preventative health. It's quite possible that one day such companies will "prescribe food" for obesity, high blood pressure, allergens, and even diabetes. The future strategically integrated companies will be driven by their control of knowledge assets to exploit whatever competitive advantage it affords.

As the future unfolds, regulatory policies will become even more important. One consumer survey after another has demonstrated that the credibility of regulatory regimes will continue to be a serious concern. Here in the United States there are specified jurisdictions for the Environmental Protection Agency (EPA), Food and Drug Administration (FDA) and the USDA. The USDA has jurisdiction over what is safe to grow, the EPA has jurisdiction over what is safe for the environment, and the FDA has jurisdiction over what is safe to consume. In Europe, the Frankenfood phenomenon emerged in part because the general public has little faith in the European Union's regulatory regime. This is not to say that the United States has escaped controversy. A flash point of controversy is the debate about consumers' rights to information regarding genetically modified foods. The basic premise that consumers deserve mandatory labeling of engineered food products is widely accepted by the general public. The task of educating the general public, however, about the distinction between genetically modified and non-modified foods is daunting. Currently consumers have little basis for assessing the potential health impacts when choosing among the myriad of products on retail shelves or making other daily choices. As numerous studies have shown, the public risk perception and views of potential health hazards from food consumption differ significantly from the views of experts (Antle, 1999).^x

On the global trade front still another policy force is represented by the World Trade Organization (WTO). Under the weight of the biotech food controversy, the WTO is now under serious public attack from unexpected sources. The fundamental issue no longer turns on the benefits from trade versus the special protectionist interest. Instead, the organic agricultural and food interests have argued that the WTO is nothing more than a shield to protect corporate profits. On this score, these interests have aligned with the protectionist's interest here in the US and elsewhere throughout the global community. When this is combined with concern about national sovereignty, the weight of anti-genetically-modified food activists could well be strengthened. The capacity for the WTO to drag and cajole entrenched interest around the world into a global trading system that operates by internally consistent rules will continue to be seriously challenged as the new century begins.

Not only will U.S. and international public policy continue to be a major force, but society could significantly benefit from private sector institutional arrangements for access to knowledge assets. The cost of litigation resulting from the award of overly broad patents, patent fragmentation, freedoms to operate, and the lack of well-articulated property rights beg for the introduction for new institutional arrangements. The prisoner's dilemma problems that have emerged over the course of the 1990s have been revealed in the exorbitant litigation cost associated with the patent infringement suits of one type or another. Institutional clearinghouses for intellectual property and technology is a first step with private sector patent pooling institutional structures representing a long-run potential solution.

The last major force identified here relates to the timing of output trait commercialization. Until now, as we all realize, the commercialization spotlight has been on input traits (B.t., and Roundup ready). These transgenic commercial products have proven to be "low hanging fruit." Public concern can be reasonably expected to shift dramatically as new output trait technologies are commercialized. The subset of traits that consumers can feel and touch can be expected to significantly transform public alarm about genetically modified foods. In this respect, output traits that focus on enhancing processing efficiency will not do.

The development of nutraceuticals and the market for prescription foods will require complementary information technologies. Here the development of niche markets are possible that are Web integrated between customers with specific differentiated demands for preventive health foods and the segments of the farming component that can generate such products. Although recent progress in nutritional genomics is promising, the future for these commercial

developments is not immediate. Breakthroughs on this front could provide significant societal and moral benefits.

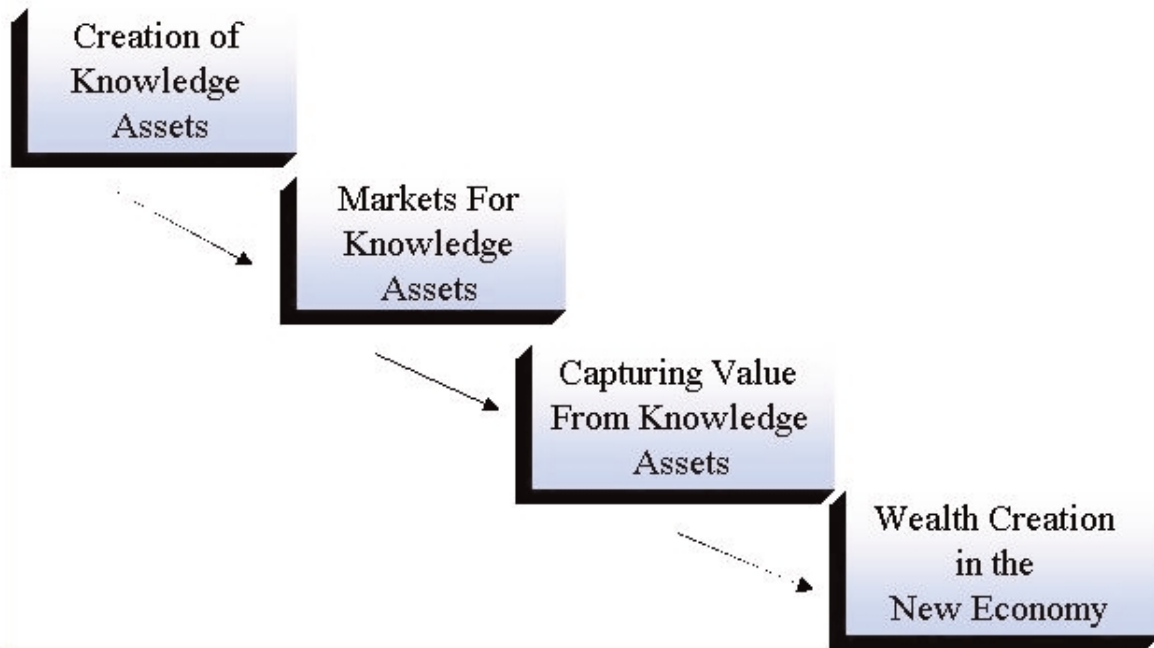
If we could write on a clean sheet of paper, the optimal sequencing would begin with nutraceuticals or prescription foods that solve serious human health problems, especially those of the poor in developing countries. This would change the direction of current public fears about genetically modified plants and food. From this platform, wide spread public and consumer acceptance of agricultural biotechnology research could more easily emerge. With such developments as background, the general public and most consumers could embrace the other benefits of agricultural biotechnology; better tasting foods, more productive and disease resistant plants, the use of plants as chemical factories, and products with improved shelf life and enhanced processing efficiency.

Conclusion

We have witnessed an unparalleled information technology revolution and are on the verge of discovering the biological essence of life. Plant genomics, animal genomics and nutritional genomics could, along with existing information technologies, provide the platform for not only pursuing but also achieving an enriched set of complementarities between economic well-being and environmental quality. To get from "here" to "there," tracking closely a virtuous cycle, requires an augmentation in the available "social capital." Life-science advancements, especially biotechnology, have revealed that societies stock of shared values, principally manifested by trust, has not fared well in many communities throughout the world. As a profession we have a role to play in enhancing the incentives and institutional arrangements for the creation of knowledge; in enhancing the incentives and institutional arrangements for well functioning technology markets; in enhancing the incentives and institutional arrangements for capturing the value of knowledge assets; and in enhancing the public's understanding of the benefits and costs of transgenic foods. It is in the latter category that our current incremental social value is perhaps the greatest.

To understand and positively influence, through public policy, the future structure of ARES, our profession must embrace all that modern economics, modern finance, and modern industrial organizations has to offer. We must become intimately familiar with both the risks and the benefits of emerging science and technology. Our existing analytical frameworks must be extended to include (a) critical non-convexities and possible increasing return regimes, (b) irreconcilable beliefs, not just the conventional asymmetric information formulation, and (c) the design of mechanisms for systematically setting in motion the convergence path for perceived and objective risk. Perhaps our greatest challenge as a profession will be to provide guidance for a distribution of knowledge that serves a well-articulated public interest.

Figure 1: Roadmap



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ENDNOTES

ⁱ Private/public collaborations in research have grown in importance, not only at research universities, but with the passage of the 1980 Stevenson-Wydler Technology Innovation Act and its 1986 amendment, the Federal Technology Transfer Act for Federal Research Agencies. The 1986 Act established a mechanism, CRADA, through which federal and non-federal researchers can collaborate.

ⁱⁱ The issue of how to structure such agreements will continue to be an important societal question. As reported by Mike Champness, the amount of money spent by industry at colleges and universities in 1997 was more than seven times as great as in 1970. This compares with all industry R&D expanding by three and one half times between 1970 to 1997. Even though the amount spent by the federal government on R&D stayed relatively constant over this period, the amount allocated by the federal government to R&D at colleges and universities increased by two and one third from 1970 through 1997. According to the Industrial Research Institute, industry funding of university research is expected to more than double over the next decade.

ⁱⁱⁱ In this regard, the agricultural biotechnology industry may have much to learn from the oil refining industry as well as the semiconductor industry.

^{iv} This section relies heavily on my collaborative research with Rachael Goodhue, Greg Graff, Susann Scotchmer, Art Small and Leo Simon.

^v With respect to *Proposition 4*, the policies reflected in the Bayh-Dole Act, 1980, the Stevenson-Wydler Technology Act of 1980 and the Federal Technology Transfer Act of 1986 have strengthened the ability of universities and governmental research agencies to diffuse technologies. Because these institutions are generally technology suppliers with no downstream assets, a societal benefit emerges from inducing final producers to diffuse their technologies with related positive effects on investment, reduction of entry barriers, and thus more competition. The fear is that such societal gains come at the cost of some unintended consequences resulting from potential deleterious impacts on open access to the development of new knowledge.

^{vi} Just as a catalog helps a library patron to focus quickly on those few volumes that are most likely to contain information she desires so can an ecological model parse the living world into categories suggesting potential use.

^{vii} For example "field research" refers to the extensive breeding programs of multiple stations that are operated by national companies. Specifically, Pioneer has fifty seed research stations in the United States and Canada, twenty-five which conduct research on corn. It has forty-three research locations outside the United States. DeKalb has thirty-six research in the United States and Canada. In addition to the national seed company breeding programs, approximately twenty-five to thirty regional seed companies have breeding programs.

^{viii} Of course this distinction is unnecessarily stark. More realistically think of the weakly articulated property right regime as representing the period when agricultural intellectual property was weakly protected under the PVPA and of the well-articulated regime as representing more recent history where property rights are articulated through utility patents.

^{ix} This field may reveal that the environmental economics many of us practice (external contamination) pales in comparison to dietary contamination.

^x Activists have dismissed the argument that it would be enormously expensive for the food distribution system to appropriately label genetically enhanced products because of the mixing of such products with ingredients that are not so modified. Activists do not find convincing the conclusions that were drawn by then Vice President Quayle's Committee in May 1992 that generically engineered food, as judged by government science, is no different from plants bred traditionally and thus need no additional governmental scrutiny.